USDA

United States
Department of
Agriculture

**Agricultural
Research
Service**

ARS–142

October 1998

Low-Input On-Farm Composting of Grass Straw Residue

in cooperation with the Agricultural Experiment Station,
Oregon State University, Corvallis

United States
Department of
Agriculture

**Agricultural
Research
Service**

ARS–142

October 1998

Low-Input On-Farm Composting of Grass Straw Residue

in cooperation with the Agricultural Experiment Station, Oregon State University, Corvallis

D.B. Churchill, W.R. Horwath,
L.F. Elliott, and D.M. Bilsland

Churchill is project leader and Elliott is research leader, U.S. Department of Agriculture, Agricultural Research Service, National Forage Seed Production Research Center, Corvallis, OR 97331–7102. Horwath is assistant professor, Department of Land, Air, and Water Resources, University of California, Davis. Bilsland is senior faculty research assistant, Bioresource Engineering Department, Oregon State University, Corvallis.

Abstract

Churchill, D.B., W.R. Horwath, L.F. Elliott, and D.M. Bilsland. 1998. Low-Input On-Farm Composting of Grass Straw Residue. U.S. Department of Agriculture, Agricultural Research Service, ARS–142, 32 pp.

In cropping fields of grass seed, straw removal is required to promote tiller growth and reduce pest incidence. In the past, straw removal was done by open field burning, which is being phased out in many regions through legislative mandates. Composting grass residue provides a possible alternative to open field burning in grass seed and other cropping systems in which plant residue waste presents cultural management problems.

Laboratory and field studies showed that composting of grass seed straw with a C:N ratio above 30:1 was feasible without the addition of N or water beyond normal yearly rainfall. Repeated turning with a front-end loader or a straddle-type turner to encourage decomposition reduced the straw volume significantly. Two turns with a flail-type compost turner or four or more turns with a front-end loader during decomposition reduced the bulk straw volume in windrows by 80 percent. More turns reduced the straw bulk by 88 percent and influenced the quality of the end product. The cost of on-farm composting of straw ranges from as low as $47 per hectare ($19 per acre) to more than $62 per hectare ($25 per acre), depending on the equipment used for windrow formation and turning.

This report will be useful to grass seed growers in the Pacific Northwest and to professional and technical workers concerned with recycling farm products.

Keywords: carbon mineralization, composting, crop residue, C:N ratio, decomposition, field composting, microorganisms, perennial ryegrass, straw, straw composting, thermophiles

Issued October 1998

While supplies last, single copies of this publication may be obtained at no cost from Donald Churchill, USDA–ARS, National Forage Seed Production Research Center, 3450 S.W. Campus Way, Corvallis, OR 97331–7102.

Copies of this publication may be purchased from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161; telephone 703–605–6000.

Acknowledgments

The authors thank Dennis Glaser, Dwight Coon, Brian Glaser, and Wendell Manning for their advice and help with straw composting. We also thank Thom G. Edgar and Hudson Minshew for collaborative research assistance.

Contents

Tables

Figures

Introduction

Grass seed growers in Oregon's Willamette Valley produce 1 million tonnes of crop residue in the form of straw on roughly 150,000 ha of fields used for grass seed production (Young et al. 1993). Removal of this straw has been considered essential to reduce many weed and disease problems and to prevent residues from inhibiting seed production. However, mechanical removal of straw has historically been troublesome and cost prohibitive.

During the 1940s, it was discovered that burning straw in the fields helped maintain profitable yields while controlling weeds, invertebrates, and fungal diseases, and for several decades open field burning was standard practice in the region's grass seed cropping systems. More recently, public concern for the environmental consequences of open field burning led to legislation that severely restricts this practice (Young et al. 1993). Open field burning may be entirely eliminated within the next few years. Without another means of straw removal, increased potential exists for disease, insect, and weed seed problems in grass seed lots. Other forms of disposal in the field, such as shredding and chopping, have been investigated (Young et al. 1993), but none have been entirely satisfactory.

Low-input, on-farm composting of grass seed straw is an alternative to thermal and mechanical residue removal (Churchill et al. 1995). Low-input composting systems have an important role in maintaining and improving soil quality and optimizing nutrient cycling (Hornick et al. 1984). Crop residues are critical components of processes that maintain soil quality and conserve nutrients. Composting is one method of handling crop residues to reduce their volume and render them useful for agriculture.

The main obstacles for perennial ryegrass (*Lolium perenne*) straw decomposition are that the straw residue often has a C:N ratio greater than 50:1 and lignocellulose can comprise over 70 percent of the grass residue by weight (Horwath and Elliott 1996a,b). Previous theory suggests that it is often impractical to compost organic residues with C:N ratios greater than 30:1 (Gouleke 1991). The main purpose of the laboratory and field studies discussed in this publication was to determine whether crop residues such as grass straw (with C:N ratios of 50:1 or greater) can be successfully composted in the field without co-composting them with an additional N source. Chemical, microbial, and environmental changes that occur during composting were also evaluated in these studies.

Decomposition During Composting

Composting is a microbially mediated exothermic process that occurs in an aerobic thermophilic environment (Rynk 1992). Factors such as moisture, temperature, the chemical form of carbon (that is, the level of cellulose, lignins, and so forth), and the form and level of nitrogen are major variables affecting the rate of the process. For the decomposition of perennial ryegrass straw, the magnitude and rate of microbial activity and byproduct production is expected to be slow compared to rates for materials such as food waste or grass clippings.

The initial stages of plant residue decomposition are characterized by the mineralization of labile components, leaving refractory components intact (Reinertsen et al. 1984, Stroo et al. 1989, Kogel-Knabner 1993). In the later stages of decomposition, recalcitrant components, such as lignin, are mineralized. The biodegradation of refractory substances [or substances that associate with refractory substances, such as lignin (that is, lignocellulose) or melanins] is intrinsically limited by their chemical structure—that is, conformational limitations exist between the refractory substance and degradative enzymes. (Haider 1986, Kogel-Knabner 1993). Describing the alteration and degradation of plant components during decomposition is difficult, due to limitations in methodology that make it impossible to distinguish among components or products of plant origin, microbial production, and decomposition (Paul and van Veen 1978).

Four phases (or stages) occur when composting perennial ryegrass in the field (fig. 1). In the first phase of decomposition (the mesophilic phase), the change in the organic C and N content of the substrate is based on the effectiveness of the composting method and determines the maturity of the resultant composted product. The stages of decomposition can be objectively determined by the decrease in C as volume reduction occurs with the metabolic reduction of carbohydrates to CO_2. The stabilization of the substrate to its ultimate humic product generally can be characterized by the C:N ratio.

With sufficient moisture, the second phase of composting occurs (the thermophylic phase). This phase begins in winter and can extend into early spring. For several weeks, little apparent change occurs despite adequate moisture and obvious exothermic activity. This second phase coincides with a period in which the most labile C fraction is consumed by a consortium of thermophiles, but with little effect on the lignocellulose fraction.

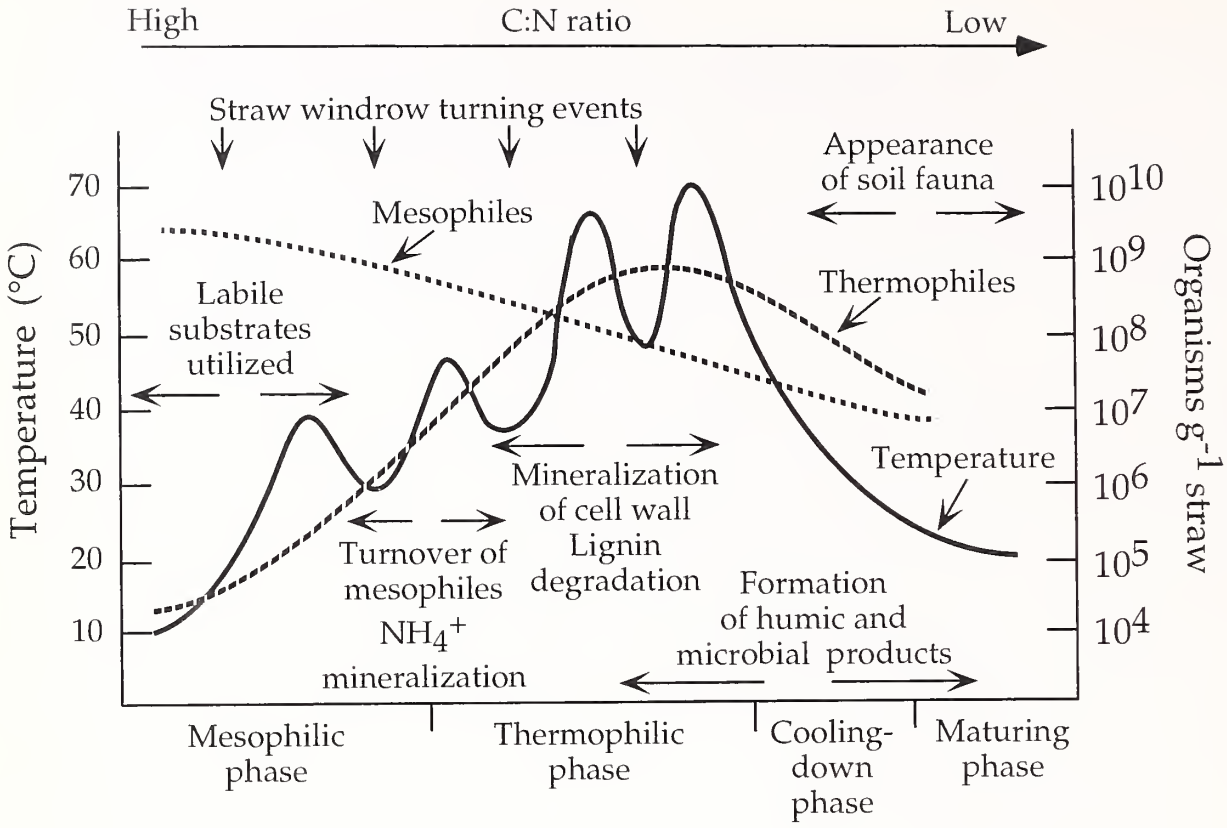

Figure 1. Summary of the four phases of field composting of perennial ryegrass and the main biological and physical characteristics that occur in each phase

The third phase of active composting (the cooling phase) starts with the advent of warmer weather in the spring. Microbiological studies have determined that thermophilic fungi and actinomycetes are instrumental in the degradation of lignin. As the lignocellulose fraction is transformed, the substrate reaches a threshold of decomposition. At this stage there are pronounced changes in the apparent texture, tensile integrity, and color (it darkens) of the substrate. Turnings at this stage cause an increase in decomposition of the straw, resulting in dramatic volume reductions in a matter of 2–4 wk.

The last phase of composting is the curing (or maturing) phase, verified when the C:N ratio reaches 12:1 to 15:1. At this point the compost can be considered "done." Cured compost continues to degrade and lose volume in the field, becoming essentially soil. Turning the substrate further will not generate increased temperatures, but may be useful to prevent saturation and to maintain a friable texture of the compost.

Laboratory and Field Studies on Straw Composting

Laboratory incubations of mature perennial ryegrass straw were conducted at 25 and 50 °C (77 and 122 °F) to simulate mesophilic and thermophilic decomposition. The 50 °C treatment was started at 25 °C for days 1–5, then raised to 50 °C for days 6–25, then lowered to 25 °C for days 26–30, and then raised again to 50 °C for days 31–45. The staggered high-temperature (HT) treatment was imposed to simulate temperature fluctuations that occur during field composting, particularly temperature losses that occur during compost turning. The level of C, H, O, N, lipids, sugars, protein, soluble polysaccharides, cellulose, lignin, CO_2 evolution, microbial biomass, bacteria, fungi, soluble C, and actinomycetes in the straw was measured during the decomposition process (Horwath and Elliott 1996a,b). Straw lignin decomposition was measured by two methods.

Perennial ryegrass straw was also composted in the field, and data from the field were collected and compared with laboratory data. Perennial ryegrass

straw was placed in nylon 32-by-32 mesh bags, and the bags were inserted into the compost stacks in the field at various depths. The samples were retrieved and analyzed at intervals during composting. Measurements of bacteria, fungi, actinomycetes, cellulose, xylanase, protease, organic N, lignin, straw lipid, sugars, protein, soluble polysaccharides, and weight loss were made on the straw samples (Horwath and Elliott 1996a,b).

Laboratory Studies

Chemical changes during decomposition

Levels of labile components (C, H, O, and N) of straw residue were monitored in our studies to determine the degree of decomposition. The concentration of C, H, and O in the straw remained similar throughout the 45-day decomposition period in both low-temperature (LT) and high-temperature (HT) treatments (table 1). The content of N in the straw during decomposition decreased from 11.2 g kg^{-1} of straw to 8.6 g kg^{-1} and 7.5 g kg^{-1} of straw in the LT and HT treatments, respectively. The content of C in the straw during degradation decreased by 175.7 g kg^{-1} and 237.1 g kg^{-1} of straw for the LT and HT straw treatments, respectively. The percentage loss of H was similar to the percentage loss of C. The loss of O was 215.8 g kg^{-1} of straw in the LT treatment and 271.6 g kg^{-1} of straw in the HT treatment. The C:N ratio decreased from 40:1 to 32:1 in the LT treatment and to 28:1 in the HT treatment. According to Biddlestone et al. (1987), mature compost C:N ratios vary from 15:1 to 20:1, indicating the decomposed straw in our laboratory study was immature.

The change in straw chemical fractions during decomposition reflects the mineralization of straw components and increases in microbial products (Paul and Clark 1989, Kogel-Knabner, 1993). All the straw components measured decreased during the LT treatment. Cellulose decreased from 562.1 g kg^{-1} of fresh straw to 297.8 g kg^{-1} of straw, representing the largest loss of all the chemical fractions measured (table 2). Lipids increased from 33.1 g kg^{-1} of fresh straw to 38.3 g kg^{-1} of straw on day 7 and then decreased to 23.5 g kg^{-1} of straw after 45 days of incubation at the low temperature. Similarly, soluble polysaccharides increased from 17.1 g kg^{-1} of fresh straw to 21.8 g kg^{-1} of straw on day 3 and then decreased to 10.1 g kg^{-1} of straw. Soluble sugars decreased from 33.0 g kg^{-1} of fresh straw to 6.9 g kg^{-1} of straw. Klason lignin steadily decreased from 121.5 g kg^{-1} of fresh straw to 113.0 g kg^{-1} of straw in the LT treatment. The initial increase in chloroform-soluble material and water-soluble polysaccharides indicates microbial production of membranes and extracellular polysaccharides (Horwath and Elliott 1996b).

Table 1. Mean concentrations of C, H, O, and N and C:N ratio in straw on day 0 and after 45 days of incubation at low temperature (LT) and high temperature (HT)

		Concentration (g kg^{-1})				
Day	Treatment	C	H	O	N	C:N
Undecomposed straw						
0		450.3 (0.7)	68.2 (0.5)	470.3 (0.8)	11.2 (0.4)	40:1
Decomposed straw						
45	LT	468.6 (10.8)	82.6 (2.2)	434.2 (13.3)	14.7 (0.5)	32:1
45	HT	467.3 (17.6)	80.6 (2.5)	435.6 (20.8)	16.5 (0.7)	28:1
Original content remaining after decomposition						
45	LT	274.6 (6.2)	48.4 (1.3)	254.5 (9.1)	8.6 (0.3)	
45	HT	213.2 (8.0)	36.8 (1.2)	198.7 (9.5)	7.5 (0.3)	

Source: Horwath and Elliott (1996b).
Note: Standard deviations are in parentheses.

Table 2. Mean chemical content of straw during decomposition at low and high temperatures

Day	Chemical composition of straw (g kg^{-1})				
	Lipids	Sugar	Soluble polysaccharides	Cellulose	Lignin
Low-temperature incubation					
1	33.1 (1.8)	33.0 (2.5)	17.1 (1.7)	562.1 (26.2)	121.5 (1.8)
3	33.7 (0.1)	13.3 (0.3)	21.8 (0.2)	542.0 (35.7)	127.9 (6.9)
7	38.3 (1.4)	9.8 (0.6)	19.0 (3.6)	481.9 (7.5)	125.6 (7.6)
12	31.5 (1.4)	8.2 (0.4)	11.4 (1.5)	450.8 (13.6)	125.1 (3.8)
20	26.9 (1.5)	7.3 (1.0)	11.1 (0.8)	381.8 (3.8)	122.2 (1.0)
30	26.4 (1.4)	7.0 (0.9)	8.9 (2.6)	312.9 (11.8)	114.1 (1.8)
45	23.5 (3.5)	6.9 (0.6)	10.1 (1.6)	297.8 (12.7)	113.0 (2.1)
High-temperature incubation					
6	43.7 (1.5)	12.6 (1.0)	13.7 (1.2)	513.8 (23.1)	119.1 (2.3)
8	38.0 (2.5)	7.5 (0.7)	12.3 (0.7)	522.2 (35.8)	119.5 (6.0)
12	35.0 (1.5)	17.9 (3.8)	9.0 (1.1)	315.8 (29.7)	109.1 (2.1)
17	30.4 (2.9)	16.7 (0.8)	8.9 (2.5)	289.0 (40.7)	106.0 (5.6)
25	26.0 (4.1)	11.6 (1.2)	6.2 (0.8)	219.4 (24.0)	102.8 (6.2)
30	25.6 (1.9)	6.1 (1.2)	6.1 (1.2)	185.5 (18.4)	102.4 (8.5)
45	18.7 (1.1)	9.7 (0.9)	5.6 (0.3)	213.8 (9.4)	89.0 (1.7)

Note: Standard deviations are in parentheses.

In the HT treatment, the straw chemical fractions were mineralized more rapidly and to a greater extent than those in the LT treatment (table 2). Cellulose decreased from 562.1 g kg^{-1} of fresh straw to 213.8 g kg^{-1} of straw. Lipids increased from 33.1 g kg^{-1} of fresh straw to 43.7 g kg^{-1} of straw on day 6 and then decreased to 18.7 g kg^{-1} of straw. Soluble sugars decreased from 33.0 g kg^{-1} of fresh straw to 9.7 g kg^{-1} of straw in the HT treatment. Soluble polysaccharides decreased from 17.1 g kg^{-1} of fresh straw to 5.6 g kg^{-1} of straw. Klason lignin decreased from 121.5 g kg^{-1} of fresh straw to 89.0 g kg^{-1} of straw.

Lignin has been reported to be the slowest of all plant components to decompose (Minderman 1968, Aber and Melillo 1991, Kogel-Knabner 1993). The Klason lignin method has been used extensively to determine lignocellulose loss in plant decomposition studies (Kirk and Obst 1988), and many ecological and agricultural field studies have used this method to determine lignin loss because of its simplicity (Kirk and Obst 1988, Aber and Melillo 1991). The Klason lignin method also has been used extensively to determine changes in substrate during composting and mushroom culture (Chang 1967, Flaig 1969, Haider 1969, Tsang et al. 1987).

Lignin C decreased 25 and 39 percent in the LT and HT treatments, respectively, as determined by elemental analysis of the Klason lignin fraction (table 3). This compared with a decline in the lignin fraction of 10 and 29 percent in the LT and HT treatments, respectively, as determined by the Klason lignin method. N in the lignin fraction increased by 12 percent in the LT treatment and 16 percent in the HT treatment (table 3). The loss of lignin H was similar to that of C in both treatments. The mass of O remained similar to that found in undecomposed straw in the HT treatment and increased to 127 percent in the LT treatment. The constant or increased level of O and loss of C and H indicated that the lignin fraction was oxidized during decomposition. Reviews of degradative reactions during lignin decomposition indicate that increases in O content occur through the oxidative splitting of side chains and oxidative ring cleavage to form carboxylic acid groups (Kirk 1971, Flaig et al. 1975, Chang et al. 1980, Crawford 1981, Kirk and Farrell 1987, Kogel-Knabner 1993).

Table 3. Mean change in element concentration in the lignin fraction of low-temperature (LT) and high-temperature (HT) treatments

	Percentage of elements remaining after degradation			
Treatment	C	H	O	N
LT	75.0 (0.4)	75.1 (0.9)	126.5 (5.5)	111.6 (9.2)
HT	61.3 (0.3)	60.0 (0.8)	98.2 (3.7)	116.1 (6.7)

Note: Standard deviations are in parentheses.

The shift in the elemental ratios of the decomposed lignin fraction indicated a greater change than that determined by the Klason method (table 4). The increased N and decreased C contents of the lignin fraction resulted in a reduction in the C:N ratio from 52.9:1 in undecomposed straw to 35.6:1 and 28:1 in the LT and HT treatments, respectively. The C:O ratio decreased from 2.4:1 to 1.4:1 and 1.5:1 in the LT and HT treatments, respectively. The C:H ratio changed little, indicating that the loss of C and H was similar in both treatments. Approximately 6 percent of the original lignin was unaltered in both treatments. The percentage of altered lignin was calculated from the change in element ratios between undegraded lignin and degraded lignin. The increased N content of the decomposed lignin suggests that humic substances are formed during decay of the straw (Flaig et al. 1975, Kogel-Knabner 1993). Other composting studies of straw residues show similar increases of N in the analyzed ligninlike fraction, using the Klason method (Bremner 1954, Flaig 1969, Haider 1969, Hammouda and Adams 1987).

Flaig et al. (1975) and Volk and Loeppert (1982) found that elemental ratios in the decayed lignin fraction closely resembled those of soil organic matter. These findings were similar to those of other studies in which different methods were used to determine lignin degradation in different plant materials (table 5). These other studies indicate that the lignin fraction was both chemically altered and contaminated with microbial products and humic substances. The result is that the lignin elemental ratios become similar to those in soil organic matter.

The composting of plant residues often leads to the accumulation of humic substances (Hammouda and Adams 1987). Horwath and Elliott (1996a,b) showed that the decomposition of lignin C, as determined by the Klason method, was greater in the HT (39 percent) than in the LT (29 percent) treatment. They also showed that the accumulation of nitrogen in the acid insoluble fraction was greater in the HT treatment (2 percent) than in the LT treatment (1.5 percent). Thus decomposition differences between the two temperatures influenced the characteristics and quality of the degradation end products.

The extensive alteration and decomposition of lignin throughout the 45 days of our recent study provides evidence of why grass straw composts successfully in the field without the addition of N to lower the C:N ratio. The results indicate that lignin was degraded concomitantly with the other straw components measured. In earlier studies, Churchill et al. (1993) found that ryegrass volume decreased by 80 percent during 20 wk of field composting. This reduction in volume would not have been possible if it weren't for the breakdown of lignin. The breakdown of lignin likely increases the availability of cell-wall polysaccharide and related compounds for microbial use (fig. 2). The relationships among the formation of humic materials, the alterations in the lignin fraction, and the production of microbial byproducts are poorly understood (Kogel-Knabner 1993). Understanding the degradation of the lignin fraction during plant residue decomposition and composting will lead to practices that can tailor the end product to specific uses and provide insights on the nature and origin of humic substances in soil.

Microbial and soluble C and N

Microbial C was similar (22 mg C g^{-1} of straw) on day 3 in both the LT and HT treatments (HT treatment maintained at 25 °C for the first 5 days) (fig. 3). Microbial C in the LT treatment remained relatively constant for 20 days and then decreased to 8 mg C g^{-1} of straw by day 45. Soluble organic C in the LT treatment was 31 mg C g^{-1} of straw on day 1 and then decreased to 20 mg C g^{-1} of straw by 45 days. The slowly declining level of soluble C indicated that a portion of this C fraction was not readily biodegrad-

Table 4. Element ratios in the lignin fraction of low-temperature (LT) and high-temperature (HT) treatments

	Mean ratio		
Treatment	C:H	C:O	C:N
Day 0	7.8	2.4	52.9
LT	7.8	1.4	35.6
HT	8.0	1.5	28.0

Table 5. Element content of straw before and after lignin degradation

Lignin	Days decomposed	Element content of straw (percent of total)			
		C	H	O	N
Perennial ryegrass*	0	64.02 (4.45)	8.19 (0.62)	26.58 (5.19)	1.21 (0.14)
Perennial ryegrass*	45	53.84 (1.07)	6.90 (0.08)	37.75 (1.06)	1.51 (0.11)
Perennial ryegrass*	45	54.78 (0.66)	6.85 (0.14)	36.41 (0.77)	1.96 (0.11)
Ryegrass†	0	63.10	5.92	30.67	0.54
Ryegrass‡	180	61.15	5.42	32.42	1.75
Ryegrass§	0	62.73	5.64	30.55	0.53
Ryegrass§	180	62.20	5.41	31.30	0.56
Wheat straw‖	0	63.39	5.41	30.98	0.22
	180	60.40	5.66	32.86	1.08

Note: Standard deviations are in parentheses.

* Horwath and Elliott (1996b).
† Freundenberg and Harkin (1964) (cited in Flaig et al. 1975).
‡ Maeder (1960) (cited in Flaig et al. 1975).
§ Flaig (1969).
‖ Flaig et al. (1975).

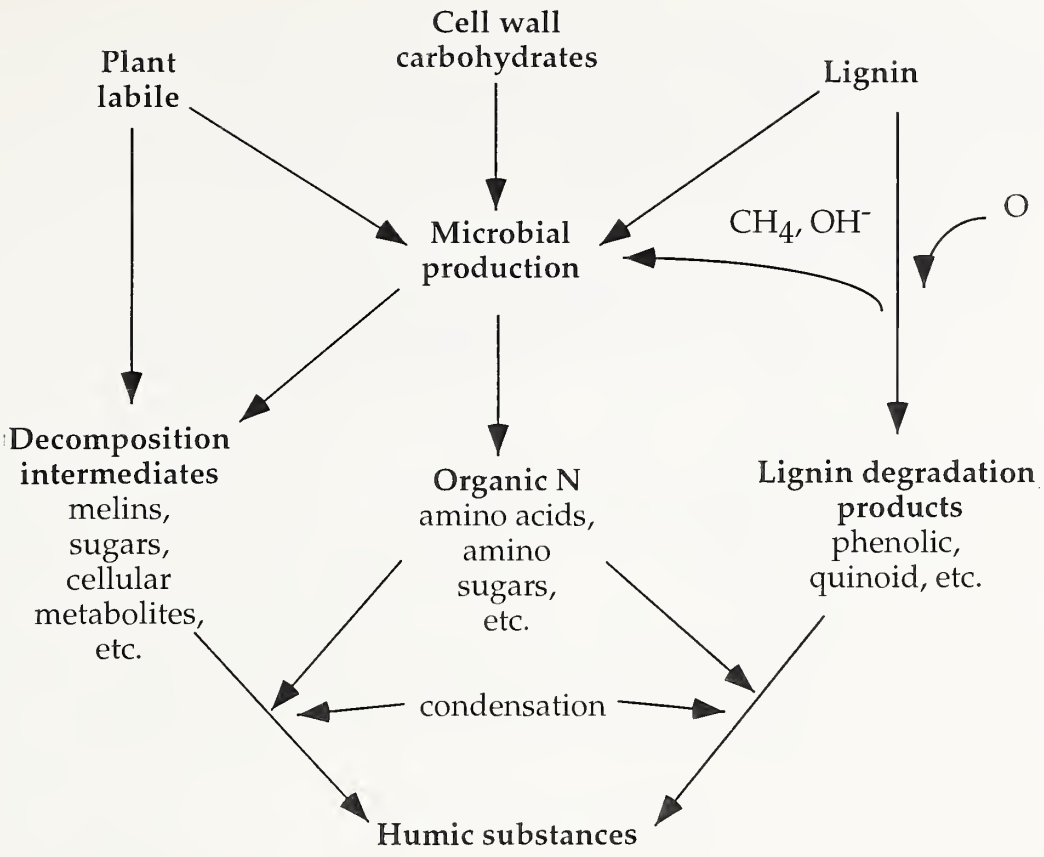

Figure 2. Proposed pathway for lignin degradation and formation of humic substances in decayed ryegrass straw

able. Microbial biomass C and respiration decreased throughout the incubation, supporting the hypothesis that there was no readily available C component.

Microbial C decreased to 4 mg C g^{-1} of straw after the temperature was increased to 50 °C. Microbial C in the HT treatment increased to 14 mg C g^{-1} of straw by day 15, remained constant to day 25, and then decreased to 4 mg C g^{-1} of straw by day 45. Soluble C in the HT treatment gradually increased to 39 mg C g^{-1} of straw after the temperature was increased from 25 to 50 °C and remained above 34 mg C g^{-1} of straw for the remainder of the HT incubation. Soluble C was approximately twice that found in the LT treatment, indicating that a greater proportion of this C fraction remained unavailable for microbial consumption in the HT treatment.

Microbial biomass N increased to 4.0 mg N g^{-1} of straw by day 3 in both the LT and HT treatments (fig. 4). In the LT treatment, microbial biomass N remained unchanged during the next 12 days, decreased to 1.7 mg N g^{-1} of straw by day 30, and increased to 2.8 mg N g^{-1} of straw at the end of the incubation. In the HT treatment, microbial biomass N decreased to less than 1 mg N g^{-1} of straw after the temperature was increased to 50 °C and then gradually increased to 2.1 mg N g^{-1} of straw by the end of the incubation. The increase in microbial N may indicate an accumulation of microbial byproducts, since microbial C decreased rather steadily in both treatments.

Soluble organic N remained below 0.5 mg N g^{-1} of straw in the LT incubation (fig. 4). Conversely, in the HT treatment it increased to 1.2 mg N g^{-1} of straw following the increase in temperature to 50 °C. The increase in soluble organic N during the transition from 25 to 50 °C on day 5 likely indicates the turnover of the mesophilic microbial population. Following the increase in temperature, soluble organic N fell below 0.5 mg N g^{-1} of straw after 20 days and remained constant for the remainder of the HT incubation.

Plating of microorganisms

Levels of bacteria, actinomycetes, and fungi for the LT and HT treatments were measured for the first 30 days of each incubation. In the LT treatment, plate counts of bacteria, actinomycetes, and fungi from the straw stabilized toward the end of the 30-day period at 10^9, 10^8, and 10^7 propagules g^{-1} of straw, respectively

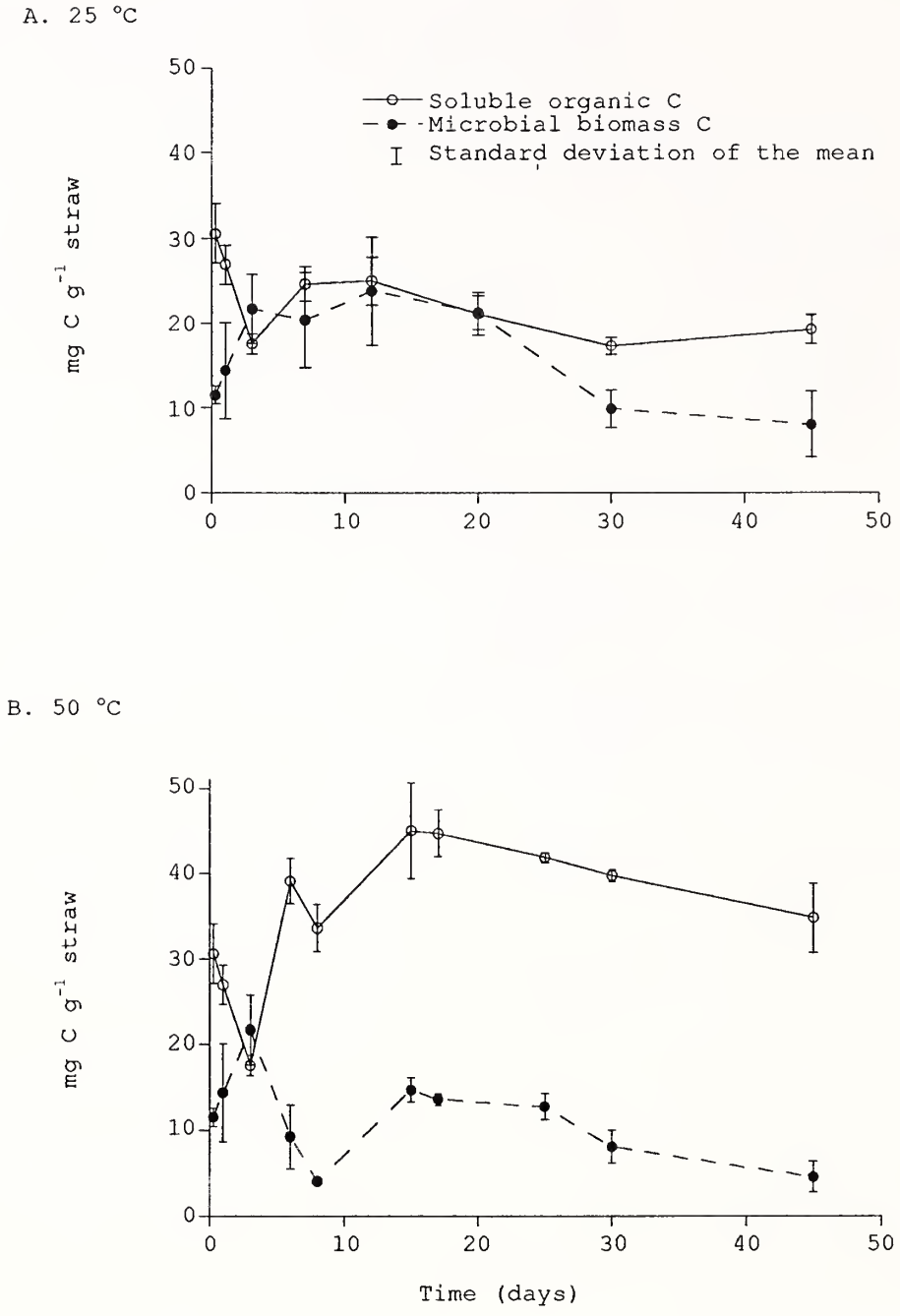

Figure 3. Microbial biomass C and soluble C levels in straw incubated for 45 days at *A*, low temperature (25 °C) and *B*, high temperature (50 °C)

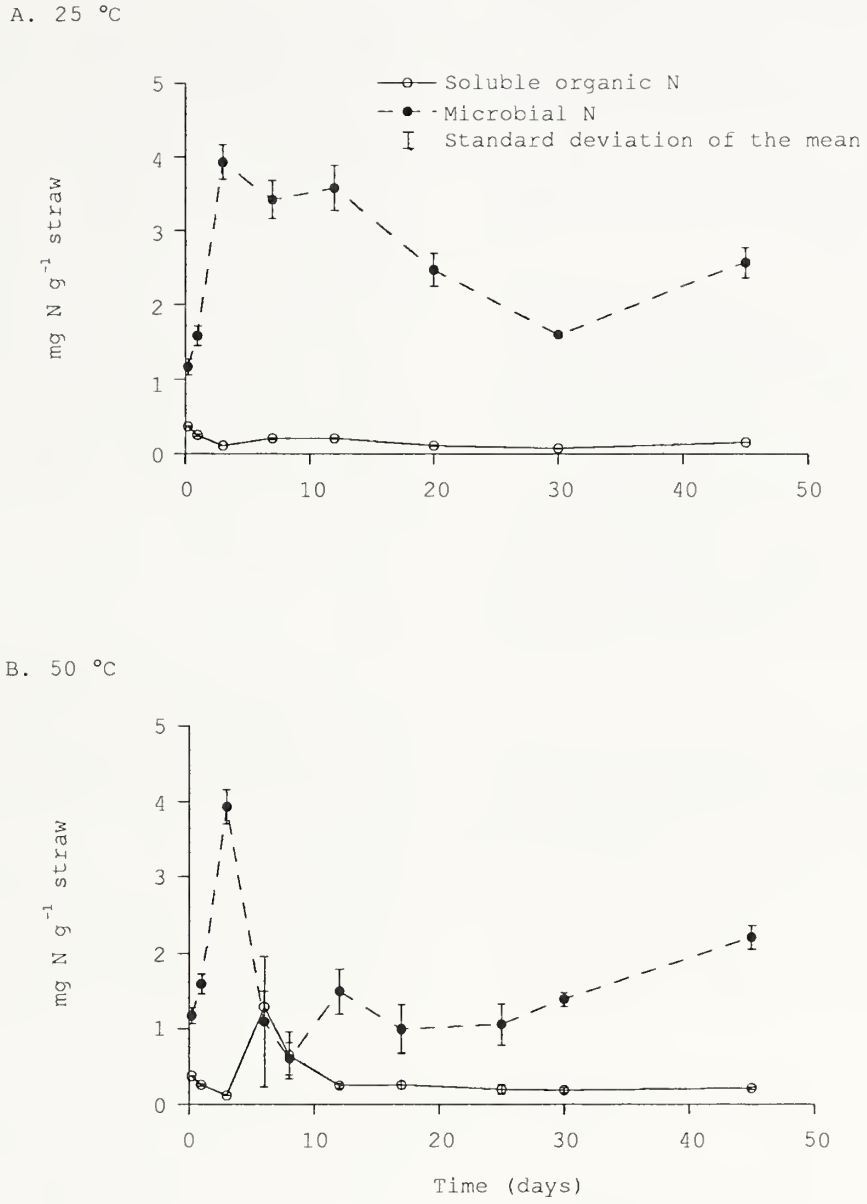

Figure 4. Microbial biomass N and soluble organic N in straw incubated for 45 days at *A*, low temperature (25 °C) and *B*, high temperature (50 °C)

(fig. 5). Actinomycetes and fungi required up to 5 days before plate counts remained constant in the LT treatment. Counts of all organisms except actinomycetes decreased when the temperature was increased from 25 to 50 °C in the HT treatment. Bacteria and fungi decreased an order of magnitude to 10^8 and 10^6 propagules g^{-1} of straw, respectively, in the HT treatment. On day 25, when the temperature was decreased from 50 to 25 °C in the HT treatment, no organisms were detected on agar plates incubated at 25 °C. The lack of microbes indicates that mesophilic organisms did not survive in detectable numbers in the thermophilic environment. The lack of thermophilic organisms at 25 °C also suggests that the organisms were obligate thermophiles.

These results showed that the inoculum potential of grass straw is sufficient to successfully degrade the straw. No additional inoculum was required to facilitate decomposition, and no additional N was needed to lower the combined C:N ratio of the straw substrate. Our initial field studies with grass seed straw composting provided similar results (Churchill et al. 1995). Adequate microbial inoculum in agricultural wastes has been demonstrated in other laboratory and field decomposition studies (Chang and Hudson 1967, Lacey and Dutkiewicz 1976, Lacey 1979, Biddlestone et al. 1987).

C mineralization

The total mineralization of perennial ryegrass straw C was similar at 25 and 50 °C during the 45-day laboratory incubation (46 percent and 52 percent of the total C, respectively). The majority of C mineralized from both of the temperature treatments (LT and HT) occurred by day 20. The addition of N to lower the C:N ratio of the straw decreased C mineralization in both treatments (fig. 6). The results indicate that maximum decomposition occurred without the addition of N.

The similarity in straw C mineralization in the LT and HT treatments without N addition can be explained by relating the C mineralization activity to microbial biomass C (fig. 7). The respiratory quotient (total C mineralized divided by microbial biomass C) for the HT treatment was approximately twice that of the LT treatment. In the HT treatment, the increased C mineralization was associated with respiratory activity, not an increase in the microbial biomass. The thermophiles required less biomass C and N than the mesophiles to decompose approximately twice as much C per unit of microbial biomass.

Successful composting of organic residues is thought to require a C:N ratio of 25:1 to 30:1 or less (Biddlestone et al. 1987). In our studies, however, the addition of N to the straw decreased C mineralization in both the 25 and 50 °C treatments. These data show that the C:N ratio of the straw is not indicative of how well straw will compost. In addition, these results show that additional N is not required to successfully compost grass straw.

The difference in microbial biomass C and N, and similar C mineralization kinetics in the LT and HT treatments indicates that substrate-use efficiency varied under the two temperature treatments. Microbial substrate-use efficiencies can decline in thermophilic regimes in response to increased metabolic rates and cell-maintenance requirements (Amelunxen and Murdock 1978). To accurately assess substrate-use efficiency, a distinction between microbial production and substrate depletion must be determined. Horwath and Elliott (1996a) reported a change in the biochemical fractions of perennial ryegrass straw incubated at 25 and 50 °C. Using their data and the C-mineralization data reported here, a simulation of microbial production and distinction between changes in residue fractions can be estimated by the following equation:

$$C=C_i[1+Y/(100-Y)] \qquad [1]$$

where

C = the amount of substrate decomposed,
C_i = the amount of CO_2–C mineralized, and
Y = the biosynthesis efficiency of the C, expressed as a percentage of the total C used for the production of microbial material (Paul and Clark 1989) (fig. 8).

Straw labile components are estimated to be used in approximately 10–15 days in both the LT and HT treatments. Approximately half of the straw cell-wall components (polysaccharides and lignin) were degraded in the HT treatment during the 45-day incubation (fig. 8). Microbial substrate-use efficiency, on a total straw basis, was 34 percent and 28 percent in the LT and HT treatments, respectively. The difference in microbial biomass size and substrate-use efficiency at 25 and 50 °C may lead to changes in the end products from the decomposition process.

Field Studies

Successful straw composting in the field requires creating an appropriate composting environment with proper moisture, aeration, and substrate nutrients so that thermophilic temperatures can be generated. The proper conditions and higher temperatures are needed to promote the growth of thermophilic bacteria and fungi that consume the straw. The higher temperatures also kill weed seeds, crop disease organisms, and insect pests. During composting, temperature readings

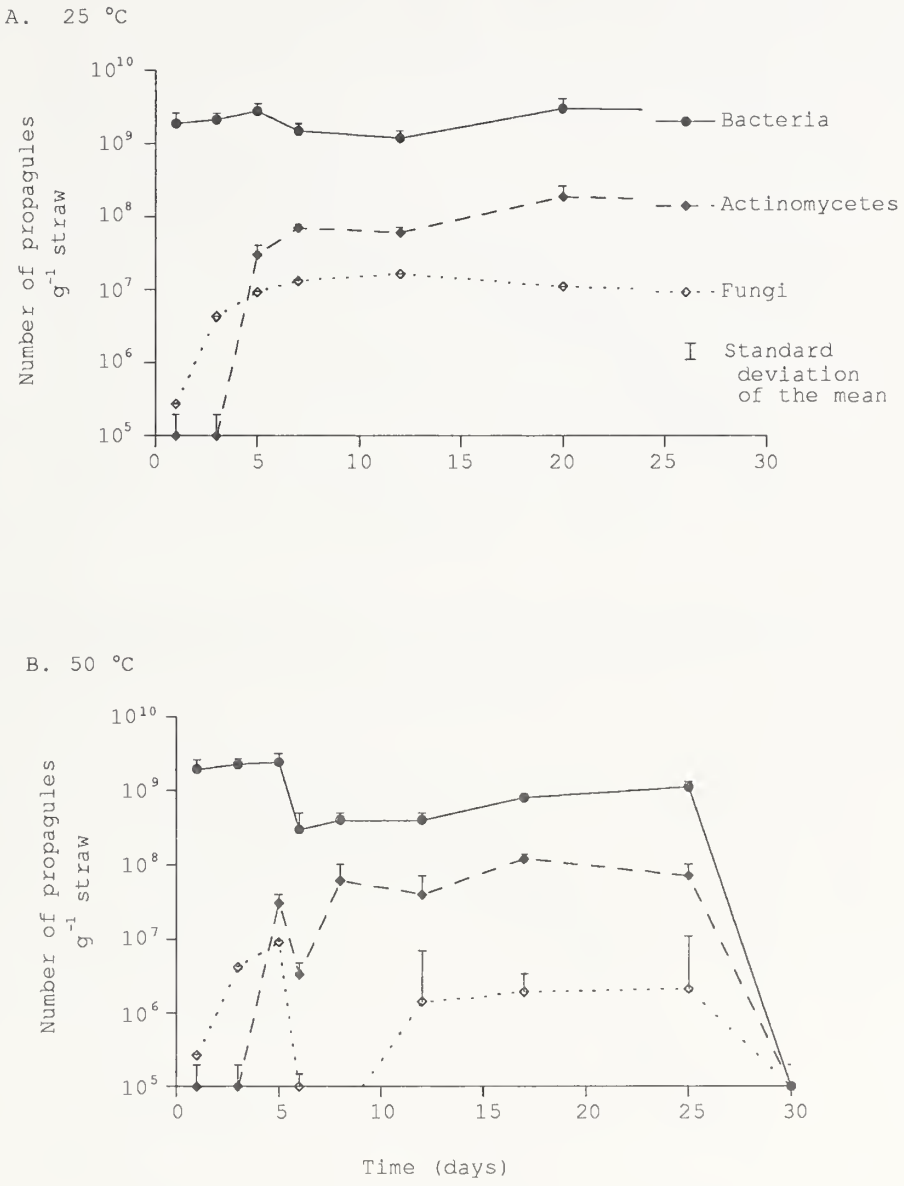

Figure 5. Number of microorganisms in straw (determined by plate count) during the first 30 days of a 45-day incubation at *A*, low temperature (25 °C) and *B*, high temperature (50 °C)

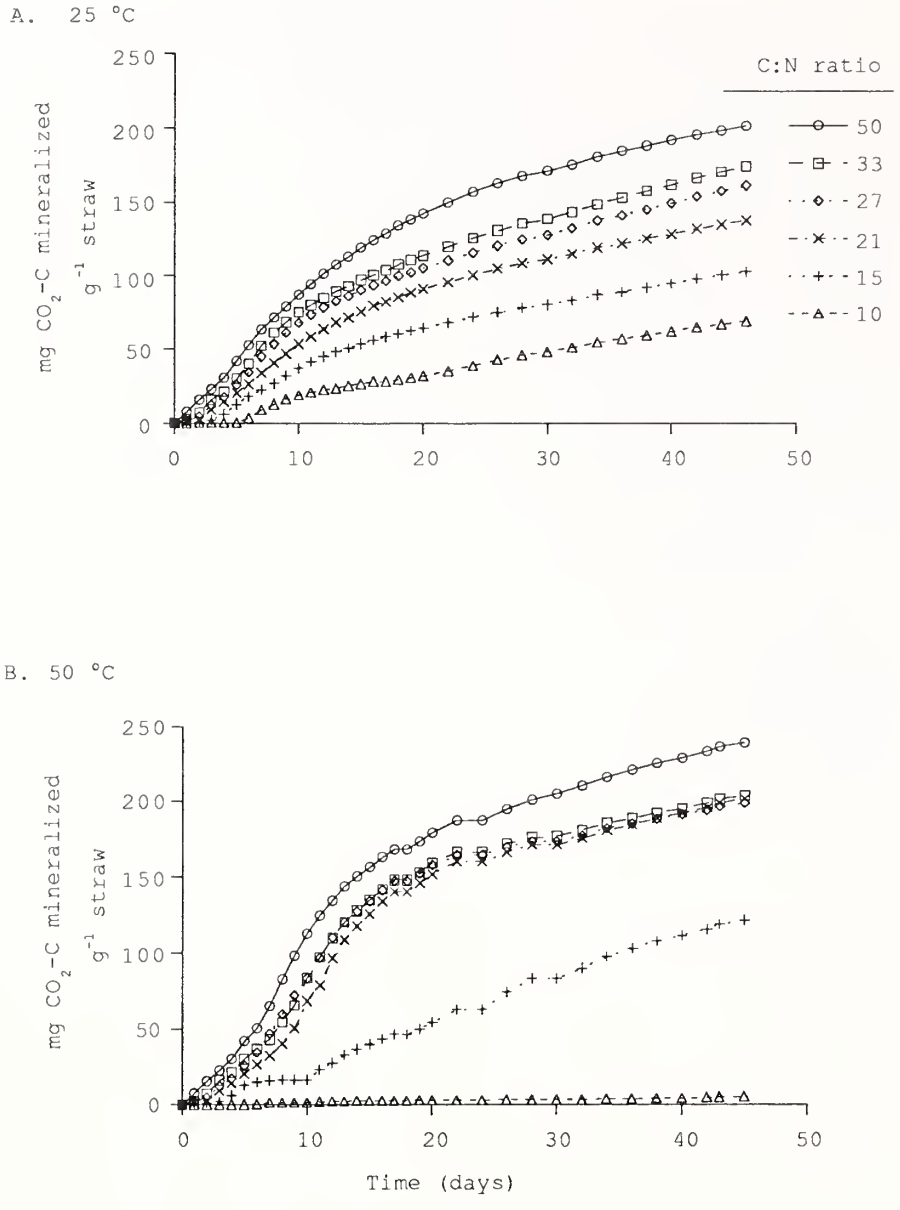

Figure 6. Mineralization of C in straw incubated at *A*, low temperature (25 °C) and *B*, high temperature (50 °C) as influenced by the addition of N during a 45-day laboratory incubation

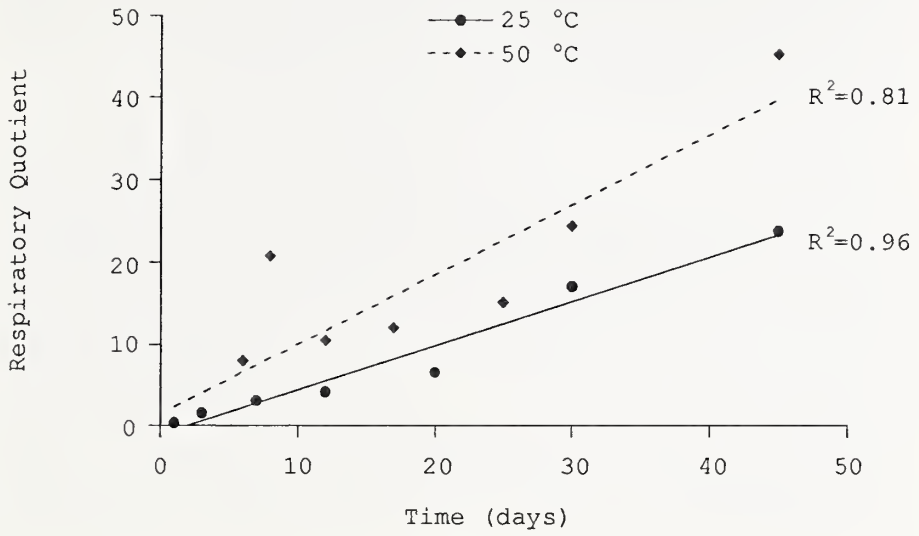

Figure 7. Respiratory quotient (mg CO_2–C g^{-1} straw divided by mg microbial biomass C g^{-1} straw) during a 45-day incubation at low and high temperature

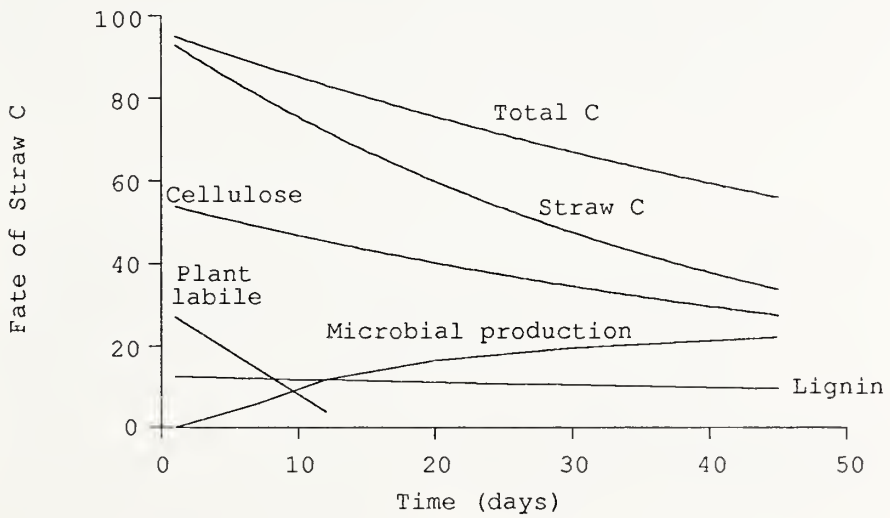

Figure 8. Simulation of microbial C production during a 45-day incubation. Cellulose and lignin degradation were determined at 25 and 50 °C (Horwath and Elliott 1996a,b). Microbial C production can be determined using equation 1.

are normally monitored on a regular basis and used to determine when and how often to turn straw composts.

Practices that alter the composting environment have a large effect on the rate and quality of composting. The field studies performed evaluate some of the effects from straw collection methods, length of straw composted (long straw versus short straw), and the number of times the compost was turned. The compost variables measured include volume reduction, temperature, moisture, and microbial and chemical changes.

Straw collection

Perennial ryegrass straw was used in the field studies. This straw is similar in chemical and physical properties to other grass straws such as those from fescue, orchardgrass, bluegrass, wheat, and rice. The straw was collected using the two most common methods available to the region's seed growers. One method was to rake long straw from the field and form windrows directly after combining. A ground-driven wheel rake and farm-built buck rake (figs. 9 and 10) were used to collect long straw and form windrows. The wheel rake can sweep a swath of 5.5–6 m (18–19.5 ft) on each pass. The wheel and buck rake can rapidly move large amounts of straw.

The other method of straw collection used was to rake, bale, and remove long straw first and then form compost windrows with only the short straw. The short straw was flailed, brushed, and vacuumed from the field using a Rear's Manufacturing Company Flail-vac machine and a John Deere stack wagon (fig. 11). Of all the procedures related to composting grass seed straw, flail vacuuming and removal of straw residues in stack wagons require the greatest equipment expense and the most time [about 2 ha (5 acres) per hr]. Typically, long-straw windrows are loose, are composed almost entirely of straw, and proportionately contain very small amounts of seed and soil. In contrast, short-straw windrows are denser, are composed of finer material, and contain relatively large amounts of soil and seed.

It is desirable to locate compost sites on the perimeter of a field where there is good drainage and easy access for turning equipment during the rainy season. Forming the straw, both long and short, into windrows is recommended to facilitate the operation of turning equipment. An important management variable in the successful composting of straw residue is aerating the material in a timely way by periodic turning. In our study, temperature was monitored to determine optimum turning times. Where product quality and rapid decomposition are factors, accessibility is necessary to enable multiple turnings based on temperature and moisture.

Windrow turning

Dry straw typically has a 10–15 percent moisture content at the end of summer. For composting, the ideal moisture content appears to be in the range of 60–70 percent moisture. After 80–100 mm of accumulated rainfall, windrows should be turned to aerate the pile and mix wet outer material into the interior and expose drier material to the surface. By doing so, the moisture content throughout the compost becomes much more uniform.

Numerous manufacturers produce compost-turning equipment with various mechanical designs. Most of this machinery is designed for the treatment of municipal organic waste solids or agricultural livestock manures. The action of a flail-type turner chops the material into smaller particles and promotes good mixing and aeration. Farm tractors used to power compost-turning machinery and self-propelled turners require a hydrostatic drive or creeper gear to allow maximum power takeoff output at very slow ground speeds. Use of compost-turning machinery is recommended where the quality of finished compost or a rapid rate of composting is an objective. However, straw residues can be successfully turned using a front-end loader (fig. 12). If a front-end loader is used, the compost pile will generally need to be turned more frequently than if a straddle turner (fig. 13) is used, but a front-end loader is effective and costs less. The straddle turner does a more thorough job of turning, thereby opening the material for uptake of water, increasing the temperature, and reducing seed and pest survival with fewer turns.

Experiments to determine the effects of the method of straw collection and number of turns on windrow volume were conducted for two seasons. During the 1992–93 and 1993–94 seasons, short-straw and long-straw windrows were formed in the same perennial ryegrass field. During the first year, turning was done with a Frontier Manufacturing straddle-type turner. In the following year, a tractor-mounted front-end loader was used for turning. Windrow plots of long and short straw were turned zero, two, four, or six times over a 9-mo period between September and June. Timing of turns was based on site access and on having at least 3 wk between consecutive turns, as fields in this region often remain inaccessible for portions of the winter and spring due to wet soil conditions.

Table 6 shows the dates of turning, the number of times the straw compost was turned, and rainfall accumulation in these studies for the 1992–93 and 1993–94 seasons. Because of the anticipated reduction in volume, three side-by-side windrows for each of the four treatments were formed at the beginning of the 1992–93 season. Windrows from the treatments turned two, four, and six times were combined into one large

Figure 9. Ground-driven wheel rake

Figure 10. Farm-built buck rake

Figure 11. Rear's Manufacturing Company Flail-vac machine and John Deere stack wagon

Figure 12. Tractor-mounted front-end loader for turning compost

Figure 13. Straddle turner for turning compost

Table 6. Turning dates, number of turnings, and rainfall accumulation in studies performed in the 1992–93 and 1993–94 seasons

1992–93 Season			1993–94 Season		
Date turned	No. of turnings	Accumulated rainfall (mm) from 8/18/92	Date turned	No. of turnings	Accumulated rainfall (mm) from 8/16/93
10/29/92	2, 4, 6	22	1/13/94	2, 4, 6	227
12/9/92	6	250	1/28/94	4, 6	256
1/13/93*	2, 4, 6	375	3/2/94	6	351
3/11/93	4, 6	511	3/30/94	2, 4, 6	397
4/20/93	6	684	5/3/94	6	467
5/17/93	4, 6	759	6/7/94	4,6	506
6/15/93		887	6/21/94		520

* The three windrows from each turned treatment (but not the 0-turn treatment) were combined into one windrow.

windrow for each treatment on January 13, 1993. During the 1993–94 season, plots turned with a front-end loader did not require combining. Temperature and volume data were collected for each straw type (short vs. long), week (1–33), and number of turns (0–6). Figures 14 and 15 show the volume reductions that occurred during the composting trial with the straddle turner. The reduction in volume in windrow plots of long and short straw was strongly related to the number of turns.

Statistical analysis of the final volume data (after 33 wk) of both types of straw showed a significant difference (p=0.05) between final volumes of compost windrows turned zero times and compost windrows turned two, four, and six times (table 7). However, no significant differences were found between final volumes of windrows turned two, four, or six times.

After the compost was turned with a straddle turner the first year, volume reduction occurred significantly faster in windrows receiving four or six turns than in those receiving zero and two turns. Volume reduction and internal temperatures were significantly (p<0.001) influenced by straw type. Higher internal temperatures and lower volume reduction occurred in windrows formed from shorter straw, probably due to its higher initial density. Volume reduction and internal temperatures were significantly (p<0.001) increased by the number of turns and by the length of time since windrow formation. An analysis of variance of individual straw types also showed significant effects of the number of turns and week on both volume reduction and temperature for short-straw (p<0.001) and long-straw (p<0.001) composts.

In the following year, composts were turned with a front-end loader, and volume reductions in both long-straw and reclipped-straw windrows were estimated to be near 80 percent in windrows turned 4 and 6 times and 50 percent in the unturned windrow. These figures were somewhat lower than those obtained the previous year when a straddle-type turner was used. Four turns with a straddle-type turner were sufficient to thoroughly break down the straw. But six or more turns with a front-end loader were required before the straw was thoroughly broken down. Timing of turning and rainfall events also affected rate of straw breakdown.

Temperature

During composting, it is desirable to maintain the thermophilic activity (in excess of 49 °C) in as much of the material as possible and for as long as possible to promote the most rapid decomposition of substrate and to decrease disease organisms and weed seed survival. In commercial and municipal composting operations, the aim is to sustain temperatures between 54 and 71 °C. Mesophilic organisms present under normal ambient temperatures are overcome by competition with thermophiles at higher temperatures. Temperatures in excess of 77 °C have been measured in composting straw, but this temperature is at the upper limit for thermophiles. Such extremes actually inhibit a more diverse microbial population from being active. When the temperature no longer increases to thermophilic levels after turning, the material has decomposed to the point of no longer providing the substrate and nutrients required to sustain a rapid rate of microbiological activity. At this point the compost is stabilized or "done."

Table 7. Percentage of original volume remaining after 33 wk of composting long and short straw

No. of turns	Percent of original volume remaining	
	Long straw	Short straw
0	47	53
2	18	42
4	17	25
6	12	20

Temperatures exceeding 50 °C were typical in windrow composts and occurred in both the long-straw (LS) and reclipped-straw (RS) treatments (fig. 16). Temperatures of up to 70 °C were observed at depths of greater than 120 cm during windrow composting (Churchill et al. 1995). The RS treatment was turned twice, and the LS treatment was turned four times. The RS treatment achieved higher initial composting temperatures during the first two turns. The temperatures in the LS treatment increased after the last two turns and exceeded those in the RS treatment. The temperature of the control treatment, which was never turned, gradually rose from approximately 10 to 25 °C during the composting period in conjunction with seasonal temperatures. The RS treatment had shorter lengths of straw and therefore a higher bulk density, which may have caused an insulating effect that may explain the differences in temperature between the RS and LS treatments.

The variation in temperature in a single profile can span 20–50 degrees. Turning causes greater substrate uniformity and improves the chance that all material will receive some exposure to the hottest conditions. All of the windrows that were turned exhibited thermophilic temperatures at some point. Figures 17–19 show the average high internal temperatures of long-, short-, and reclipped-straw windrows turned different

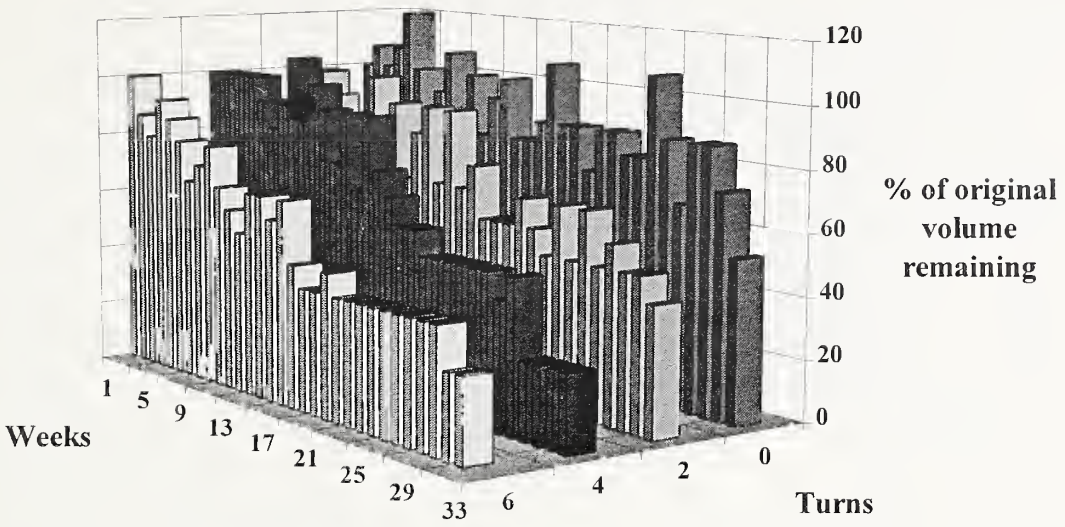

Figure 14. Percentage of original volume remaining in short-straw windrows receiving zero to six turns. Volume measurements over 100 percent were due to additional air space after turning, resulting in a fluffed-up substrate.

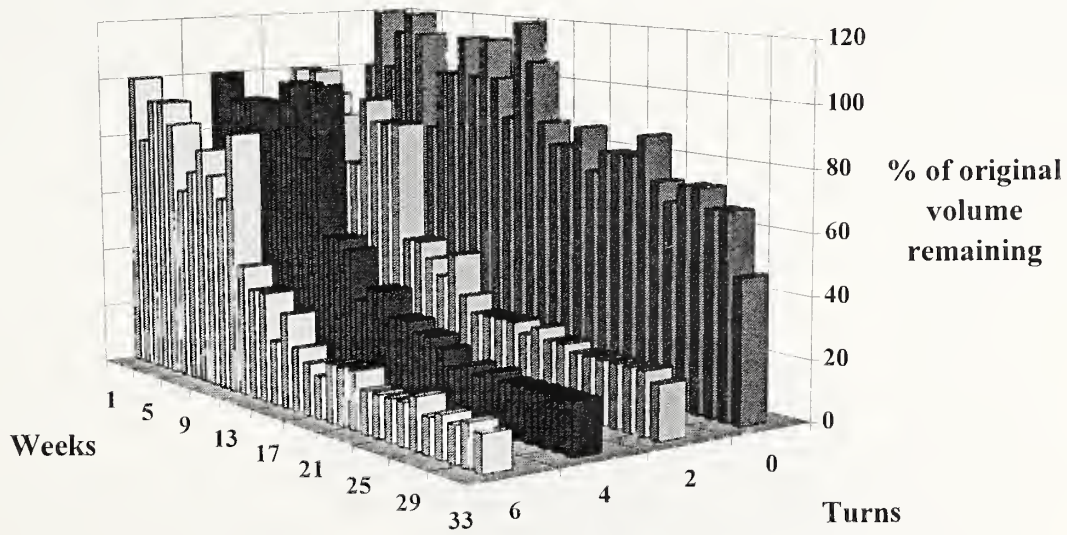

Figure 15. Percentage of original volume remaining in long-straw windrows receiving zero to six turns. Volume measurements over 100 percent were due to additional air space after turning, resulting in a fluffed-up substrate.

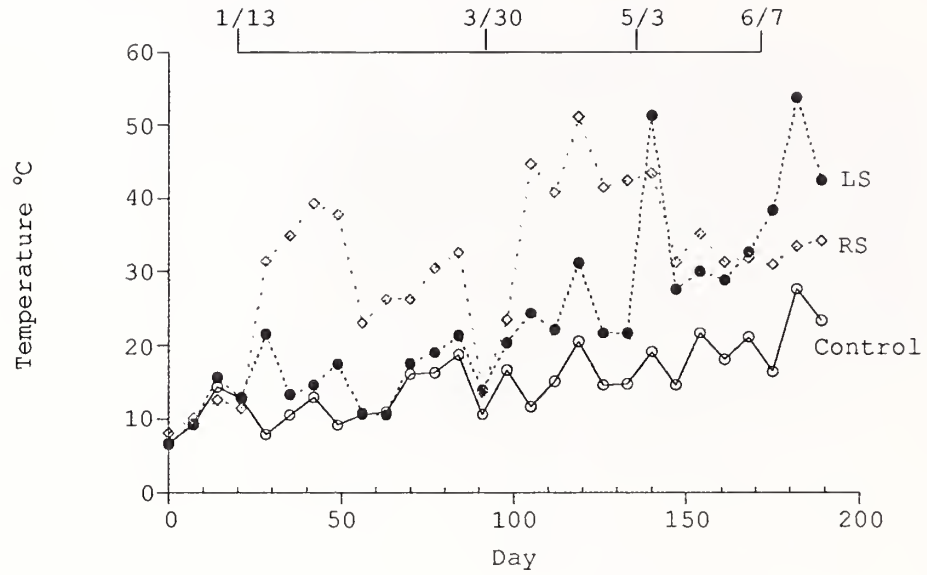

Figure 16. Maximum temperatures in windrow composts from December 19, 1993, to July 28, 1994, for control, long-straw (LS), and reclipped-straw (RS) treatments. Dates (at top) indicate when composts were turned.

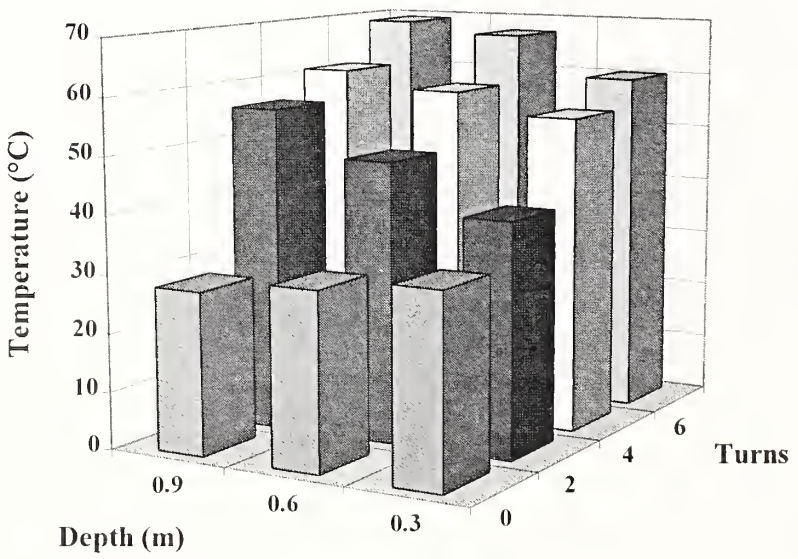

Figure 17. Average high internal temperature of long-straw windrows at different depths with different numbers of turns

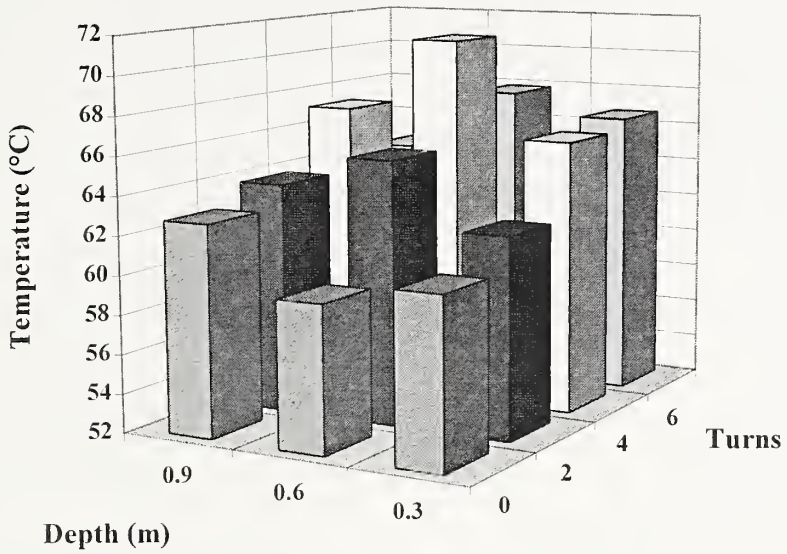

Figure 18. Average high internal temperature of short-straw windrows at different depths with different numbers of turns

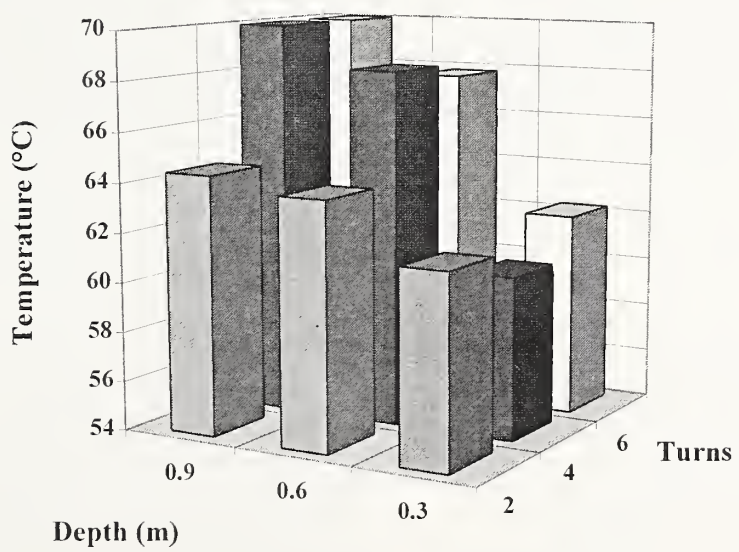

Figure 19. Average high internal temperature of reclipped-straw windrows at different depths with different numbers of turns

numbers of times using a front-end loader. These figures show an increase in temperature for all three types of straw with each additional turn and show that the highest temperatures tend to occur at greater depths. The increased temperatures are conducive to greater microbial activity and further breakdown of straw lignin and cellulose.

Internal temperatures high enough to ensure that all seeds were completely killed were never reached for either type of straw, although temperatures over 49 °C did occur several times. Use of this compost should therefore be limited to instances where the presence of viable crop and weed seed is inconsequential or where volunteer seedlings can be controlled.

Microbiological and chemical changes during field composting

The difference in windrow temperatures, number of turns, and initial C:N ratio among the windrow treatments had little or no effect on the number of culturable mesophilic organisms in the straw (fig. 20). Mesophilic bacteria were present in the largest numbers, attaining densities of 10^8–10^9 colony-forming units (cfu) per g (dry wt) of straw. Mesophilic actinomycetes and fungi were present in numbers between 10^6 and 10^8 cfu per g of straw. During the latter stages of windrow decomposition, as the LS and RS treatments increased in temperature, thermophilic bacteria increased to 10^7–10^8 cfu per g of straw, and thermophilic actinomycetes and fungi increased to 10^5–10^6 cfu per g of straw. In the control treatment (data not shown), thermophilic populations of bacteria, actinomycetes, and fungi remained unchanged at 10^3–10^4 cfu per g of straw, 10^2–10^3 cfu per g of straw, and 10^2–10^3 cfu per g of straw, respectively. The populations of microorganisms in the perennial ryegrass windrows were similar to those observed in wheat and hay composts (Chang 1967, Lacey and Dutkiewicz 1976).

Cellulase, xylanase, and protease activity did not present definable patterns (data not shown). The measurement of potential hydrolytic enzyme activity appears to have limited value in interpreting straw decomposition and completeness or quality of the end product.

Klason lignin increased or remained unchanged in all treatments and depths (data not shown, see Horwath and Elliott 1996a). Elemental analysis of the Klason lignin fraction revealed extensive C loss and accumulation of O and N (table 8) and showed that the lignin fraction was substantially altered. We observed a greater or equal loss of lignin fraction C than in previous laboratory incubations of straw (Horwath and Elliott 1996b). The straw residue in the deep LS treatment lost 55 percent of the original lignin fraction C content (table 8). The loss of lignin fraction C in the other treatments was 16–40 percent of the original lignin C. Deep straw residue samples lost more lignin fraction C than shallow samples for the LS treatment, but depth did not affect lignin fraction C for the RS treatment. The increased loss of the lignin fraction C in both depths of the RS treatment and in the deep straw samples of the LS treatment was associated with higher windrow temperatures, which indicated the importance of thermophiles in lignin degradation.

The increased N content of the lignin fraction was associated with the accumulation of humic substances (Hammouda and Adams 1987). The lignin fraction N content of all treatments increased between 1.5 and 2.4 times the original lignin N content (table 8). Treatment and straw type influenced the amount of N stabilized in the organic fraction. The four-turn LS treatment stabilized more N in organic forms than the control or RS treatments. The differences in the accumulation of lignin fraction N indicated that the treatment conditions affected the production and quality of the composted end product.

The reduced N requirement of the thermophiles shown in these studies is a unique feature of thermophile ecology that enables these organisms to degrade substrates having a high C:N ratio. The N requirement of thermophiles can also be met during the transition between mesophilic and thermophilic environments. During the transition between mesophilic and thermophilic temperatures in laboratory straw incubations, the accumulation of soluble organic N and ammonium occurred (fig. 21). The increase in soluble N and ammonium may occur as a result of the turnover of the mesophilic population. The increase in available N was three times the microbial biomass N content of the thermophilic population and indicates that sufficient N was available for the thermophilic organisms (Horwath and Elliott 1996a).

In the current study, the increase in thermophiles coincides with the gradual increases in windrow temperature in the LS and RS treatments (fig. 16). The turnover of the mesophilic population during thermophilic activity may be an important mechanism that supplies a limited pool of N for thermophilic microorganism activity. The C:N ratio of the final decomposed straw in the deep samples indicates that the windrow composting treatments produced a completed compost (table 9). The LS deep treatment produced material with the lowest C:N ratio (12:1). The RS and control deep treatments had final C:N ratios of 17:1 and 18:1, respectively. The shallow decomposition samples had C:N ratios higher than 20:1, indicating that they were incompletely decomposed.

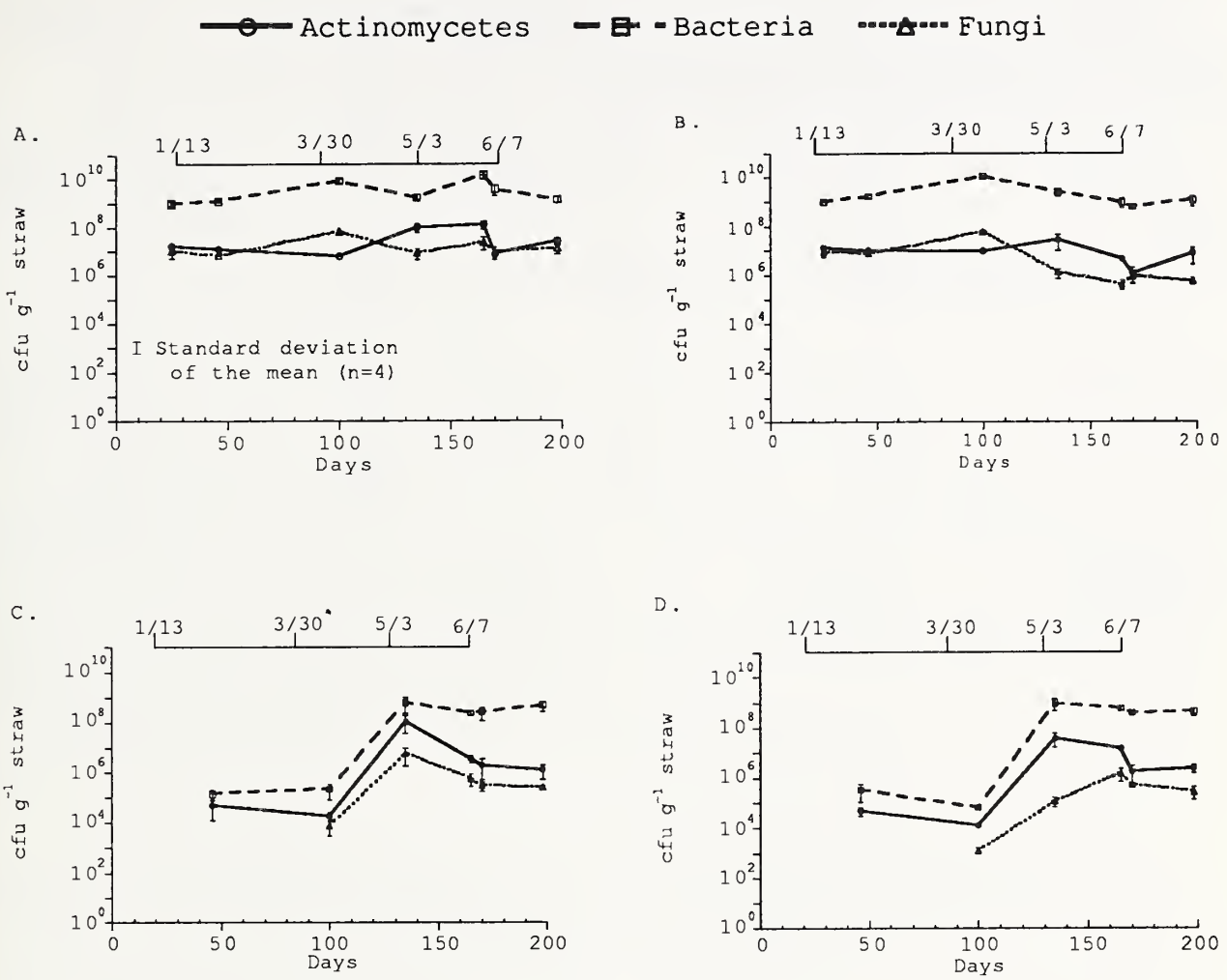

Figure 20. Density of microorganisms [expressed as colony-forming units (cfu)] for the long-straw treatment, including the populations of mesophilic microorganisms in *A*, shallow samples and *B*, deep samples, and populations of thermophilic microorganisms in *C*, shallow samples and *D*, deep samples. Dates indicate when treatments were turned.

Table 8. Percentage of C, H, and O remaining in the lignin fraction after 200 days of decomposition at shallow and deep depths of straw windrow treatments

Treatment	Percent remaining			
	C	H	O	N
Day 0	100	100	100	100
Shallow				
Control	86	82	122	197
LS*	84	83	158	239
RS†	63	54	110	154
Deep				
Control	67	63	115	152
LS	45	42	101	222
RS	60	51	153	187

* Long straw

† Reclipped straw

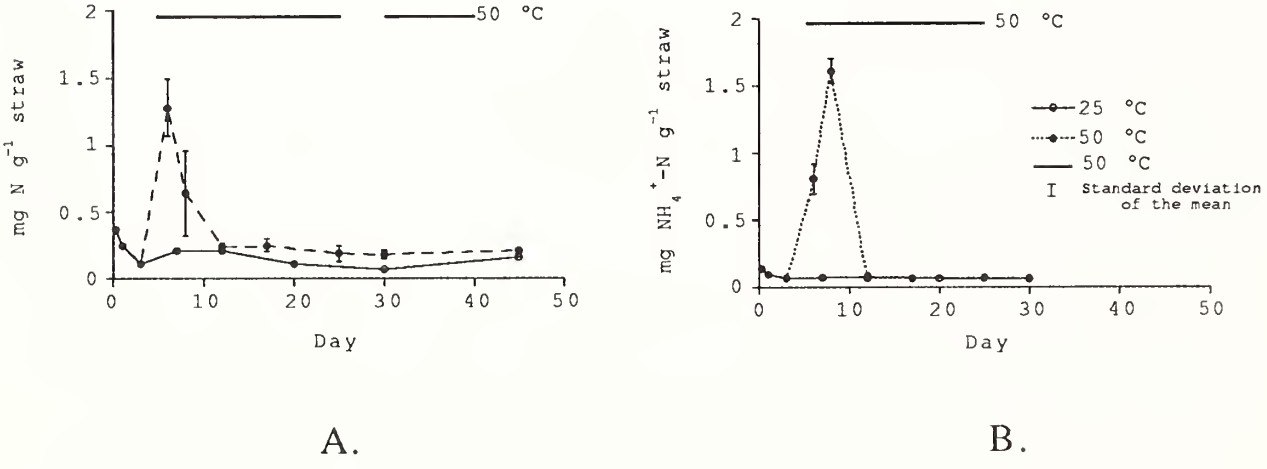

Figure 21. Accumulation of *A*, soluble organic N and *B*, ammonium during laboratory straw incubations

Table 9. Percentage of C and N and the C:N ratio before and after composting control, LS, and RS windrow treatments

Treatment	C (%)	N (%)	C:N ratio
	---------- Initial values before composting ----------		
LS windrow straw*†	40.9 (0.5)	0.78 (0.04)	52.6 (3.4)
RS windrow straw†	42.4 (0.2)	0.71 (0.04)	59.7 (2.8)
Straw in nylon bags‡	43.8 (0.2)	0.92 (0.02)	47.7 (0.9)
	-------- Values for straw in nylon bags after composting -------		
Shallow samples			
Control‡	40.9 (0.3)	1.84 (0.16)	24.0 (1.8)
LS‡	41.4 (0.8)	1.94 (0.11)	21.6 (1.4)
RS‡	43.8 (0.7)	1.95 (0.12)	22.7 (1.3)
Deep samples			
Control‡	40.6 (0.4)	2.29 (0.18)	18.0 (1.4)
LS‡	34.6 (0.9)	2.79 (0.12)	12.4 (0.1)
RS‡	40.9 (0.3)	2.35 (0.07)	17.4 (0.6)

Note: Standard errors of the means are shown in parentheses.

* Control windrow straw treatment has same values as LS windrow straw treatment.
† n=3.
‡ n=4.

Composted grass straw as a soil amendment
In these studies, the number of seeds, percent germination, percent N, and C:N ratio of long- and reclipped-straw compost changed as the compost was turned (table 10). Presence of germinable seeds partly dictates the end use of a compost, while C:N ratios indicate compost maturity and the content, form, and fertilizer value of N in the compost. The seed content of both types of compost varied considerably among samples. N content increased in both types of straw while the C:N ratio decreased as the compost matured.

Nutrient levels and availability in composts are typically low when compared to synthetic fertilizers. The value of compost is promoted in terms of its ability to release nutrients over a long period of time and return organic matter to the soil. Because these factors cannot easily be assigned a dollar value, they are generally termed intangible benefits. It is difficult to assign a dollar value to grass straw compost on the basis of its cost of production, as there are so many different methods, combinations of machinery, and potential yields possible from one field and farm operation to the next. Estimates of the nutrient reclamation value and economic worth of grass compost as fertilizer are presented in tables 11 and 12. The data from these tables are averages from three sites on which short straw was composted and two sites on which long straw was composted. The composts were analyzed for levels of N, P, K, Ca, and Mg after 7 mo of composting. Table 11 presents the results in kg of nutrient per dry tonne of compost. Based on the average nutrient content of straw (from table 11) and the average costs of various fertilizer nutrients, the value of grass straw compost is about $18.40 per dry tonne, as summarized in table 12.

Survival of seed and seed disease organisms
Temperatures sufficient to kill seeds were noted in some locations in both types of straw. However, the average internal temperature of the composts was well below the suggested 66 °C necessary for killing all seed. Since windrows created from long straw are of low density, the heat necessary for composting this material is easily lost through cold-air infiltration.

Number of turns, straw length, and internal temperature of the compost affected the survival of all seed species (table 10) and seed disease organisms. Survival decreased as the number of turns increased and as temperatures increased. The high and average temperatures in the compost were affected by the

Table 10. Physical properties of long and reclipped straw receiving different numbers of turns

Straw type and no. of turns	Seeds g^{-1} compost	Germination (%)	Nitrogen (%)	C:N ratio
Long straw				
0 turns	4.07	88.8	0.90	48.62
2 turns	2.87	47.93	1.31	35.29
4 turns	5.98	11.33	—	—
6 turns	—	—	—	—
Reclipped straw				
0 turns	1.43	93.41	0.75	57.37
2 turns	1.18	67.85	1.19	38.18
4 turns	0.68	37.83	—	—
6 turns	—	—	—	—

Table 11. Nutrient content of grass straw compost made from short and long straw

Straw type	Nutrient content (kg $tonne^{-1}$)				
	N	P	K	Ca	Mg
Short	14.4	0.24	7.8	3.7	0.9
Short	16.4	0.34	8.0	4.3	1.4
Short	20.50	0.40	11.6	2.9	1.3
Long	14.6	0.39	15.9	1.5	1.3
Long	12.5	0.08	6.6	1.9	0.5

Table 12. Nutrient content and nutrient value of typical grass straw compost

	N	P	K	Ca	Mg	Total
	Percent					
Nutrient content	1.73	0.03	1.10	0.32	0.13	
	Dollars					
Fertilizer value kg^{-1}	0.53	3.24	0.49	0.05	0.11	
Nutrient value $tonne^{-1}$	10.10	1.07	5.94	1.13	0.16	18.40

number of turns, straw length, depth, and interaction of these variables. Blindseed was most susceptible to turning; none of them survived after two or more turns. Tall fescue seed was most resistant to the effects of turning, with a small percentage surviving six turns in some cases.

Cost Estimates of Field Composting

Total costs for short-straw windrow composting, including preparation and turning, range from \$60 ha^{-1} to over \$80 ha^{-1}. Straw collection with Flail-vac and stack wagon machinery represents \$50–\$55 ha^{-1} of the total costs. Total costs for long-straw composting range from \$47 ha^{-1} to over \$62 ha^{-1}. Straw collection with wheel and buck rake combinations represents about \$30–\$40 ha^{-1} of the total costs. These are estimated values based on field trial observations and farmer interviews (Cross 1992). Per hectare costs are based on the entire acreage from which straw is removed, not the limited area used as the composting site. Actual costs vary with differences in machinery, machinery operator, and weather and field conditions. Field-trial costs for turning compost in 1993–94 with a front-end loader were considerably less than those of the previous season when a straddle-type turner was used.

Conclusion

The extensive alteration and decomposition of lignin and the reduced N requirement of the thermophilic biomass provides evidence for why grass straw successfully composts in the field without the addition of N to lower the C:N ratio. In laboratory studies, it was shown that the breakdown of lignin likely increases the availability of cell-wall polysaccharide and related compounds for microbial use. In the composted straw, the available C was required by thermophiles because of their lower substrate utilization efficiency. The field experiments indicated that lignolytic wastes can be upgraded to form high-quality organic amendments with low C:N ratios. Treatment and straw quality influenced the final C:N ratio of the straw compost and indicates that straw management can be changed to achieve different-quality end products.

It is evident from the on-farm composting research and from analyzing the characteristics of grass straw compost that it is necessary to aerate compost material by turning. As few as two or three turns can be applied to both short- and long-straw windrows to achieve near-maximum volume reduction. Volume reductions of 80–90 percent can be achieved with relatively low-input when given a timeframe that extends throughout the winter.

The straw-composting methods described serve as an alternative to field burning and traditional on-site residue management techniques that are often associated with residue inhibition and pestilence. These methods can be integrated into a sustainable cropping system. On-farm composting is immediately practicable on grass seed farms that have the straw-handling equipment with which to clear a field of postharvest residue.

References

Aber, J.D., and J.M. Melillo. 1991. Terrestrial ecosystems. Saunders College Publishing, Philadelphia.

Amelunxen, R.E., and A.L. Murdock. 1978. Microbial life at high temperatures: Mechanisms and molecular aspects. *In* D.J. Kushner, eds., Microbial Life in Extreme Environments, pp. 217–278. Academic Press, New York.

Biddlestone, A.J., K.R. Gray, and C.A. Day. 1987. Composting and straw decomposition. *In* C.F. Forster and D.A. Wase, eds., Environmental Biotechnology, pp. 135–175. John Wiley and Sons, New York.

Bremner, J.M. 1954. Nitrogen transformation during the biological decomposition of straw composted with inorganic nitrogen. Journal of Agricultural Science 45:469–475.

Chang, Y. 1967. The fungi of wheat straw compost. II. Biochemical and physiological studies. Transactions of the British Mycology Society 50:667–677.

Chang, H., C. Chen, and T.K. Kirk. 1980. The chemistry of lignin degradation by white-rot fungi. *In* T.K. Kirk, T. Higuchi, and H. Chang, eds., Lignin Biodegradation: Microbiology, Chemistry and Applications, pp. 215-230. CRC Press, Boca Raton, FL.

Chang, Y., and H.J. Hudson. 1967. The fungi of wheat straw compost I. Ecological studies. Transactions of the British Mycology Society 50:649–666.

Churchill, D.B., D.M. Bilsland, and L.F. Elliott. 1995. Method for composting grass seed straw residue. Applied Engineering in Agriculture 11:275–279.

Churchill, D.B., W.R. Horwath, L.F. Elliott, A. Hashimoto. 1993. Development of low-input, on-farm composting. *In* Agronomy Abstracts, p. 243. American Society of Agronomy, Madison, WI.

Crawford, R.L. 1981. Lignin biodegradation and transformation. John Wiley and Sons, New York.

Cross, T. 1992. Costs of owning and operating farm machinery in the Pacific Northwest. University of Idaho.

Flaig, W. 1969. Untersuchungen uber den Ligninabbau bei der Rotte von Stroh. Mushroom Science 7:127–138.

Flaig, W., H. Beutelsacher, and E. Rietz. 1975. Chemical composition and physical properties of humic substances. *In* J.E. Gieseking, ed., Soil Components: Volume 1, Organic Components, pp. 1–211. Springer-Verlag, New York.

Gouleke, C.G. 1991. Principles of composting. *In* The Biocycle Guide to the Art and Science of Composting. The JG Press, Inc., Emmaus, PA.

Haider, K. 1969. Der Bildungsmechanismus stickstoffhaltiger Huninstoffe wahrend der Rotte. Mushroom Science 7:139–147.

Haider, K. 1986. Changes in substrate composition during the incubation of plant residues in soil. *In* V. Jensen, A. Kjoller, L.H. Sorensen, eds., Microbial Communities in Soil, pp. 133–147. Elsevier, New York.

Hammouda, G.H.H., and W.A. Adams. 1987. The decomposition, humification, and fate of nitrogen during composting of some plant residues. *In* M.D. Bertoldi, M.P. Ferranti, P.L.'Hermite, and F. Zucconi, eds., Compost: Production, Quality and Use, pp. 245–253. Elsevier, New York.

Hornick, S.B., L.J. Sikora, S.B. Sterrett, et al. 1984. Utilization of sewage compost as a soil conditioner and fertilizer for plant growth. U.S. Department of Agriculture, Agriculture Information Bulletin No. 464.

Horwath, W.R., and L.F. Elliott. 1996a. Microbial C and N dynamics during mesophilic and thermophilic incubations of ryegrass. Biology and Fertility of Soils 22:1–9.

Horwath, W.R., and L.F. Elliott. 1996b. Ryegrass straw component decomposition during mesophilic and thermophilic incubations. Biology and Fertility of Soils 21:227–232.

Kirk, T.K. 1971. Effects of microorganisms on lignin. Annual Review of Phytopathology 9:185–210.

Kirk, T.K., and R.L. Farrell. 1987. Enzymatic "combustion": The microbial degradation of lignin. Annual Review of Microbiology 41:465–505.

Kirk, T.K., and J.R. Obst. 1988. Lignin determination. Methods of Enzymology 161:87–100.

Kogel-Knabner, I. 1993. Biodegradation and humification processes in forest soils. Soil Biology and Biochemistry 8:101–135.

Lacey, J. 1979. The microflora of straw and its assessment. *In* E. Grossbard, ed., Straw Decay and Its Effect on Disposal and Utilization, pp. 57–64. John Wiley and Sons, New York.

Lacey, J., and J. Dutkiewicz. 1976. Methods for examining the microflora of moldy hay. Journal of Applied Bacteriology 41:13–27.

Minderman, G. 1968. Addition, decomposition and accumulation of organic matter in forests. Journal of Ecology 56:355–362.

Paul, E.A., and F.E. Clark. 1989. Soil microbiology and biochemistry. Academic Press, New York.

Paul, E.A., and J.A. van Veen. 1978. The use of tracers to determine the dynamic nature of organic matter. Transactions of the International Congress of Soil Science 11:61–102.

Reinertsen, S.A., L.F. Elliott, V.L. Cochran, and G.S. Campbell. 1984. Role of available carbon and nitrogen in determining the rate of wheat straw decomposition. Soil Biology and Biochemistry 16:459–464.

Rynk, R. 1992. On-farm composting handbook. Northeast Regional Agricultural Engineering Service, Cooperative Extension, Cornell University, Ithaca, NY 54:1–186.

Stroo, H.F., K.L. Bristow, L.F. Elliott, R.I. Papendick, and G.S. Campbell. 1989. Predicting rates of wheat residue decomposition. Soil Science Society of America Journal 53:91–99.

Tsang, L.J., I.D. Reid, and E.C. Coxworth. 1987. Delignification of wheat straw by *Pleurotus* spp. under mushroom growing conditions. Applied Environmental Microbiology 53:1304–1306.

Volk, B.G., and R.G. Loeppert. 1982. Soil organic matter. *In* V.J. Kilmer, ed., Handbook of Soils and Climate in Agriculture, pp. 211–268. CRC Press, Boca Raton, FL.

Young III, W.C., B.M. Quebbeman, T.B. Silberstein, and D.O. Chilcote. 1994. Final report: An evaluation of equipment used by Willamette Valley grass seed growers as a substitute for open-field burning. Department of Crop and Soil Science, Oregon State University, Extension Circular S 99.